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DETECTION OF OCEAN COLOR CHANGES FROM HIGH ALTITUDES

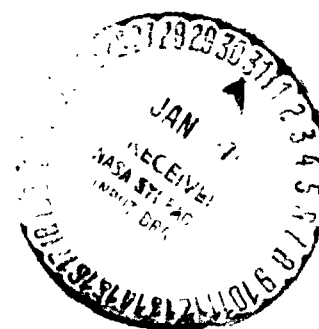
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GODDARD SPACE FLIGHT CENTER
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FROM
HIGH ALTITUDE

by

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November 1973

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ABSTRACT

The detection of ocean color changes, thought to be due to chlorophyll concentrations and gelbstoffe variations, is attempted from high altitude (11.3 km) and low altitude (0.3 km). The atmospheric back scattering is shown to reduce contrast, but not sufficiently to obscure color change detection at high altitudes.

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DETECTION OF OCEAN COLOR CHANGES FROM HIGH ALTITUDE

I. INTRODUCTION

For centuries men have noted the color of ocean water and related it to such things as fish production and silt inflow from rivers and streams. Bodies of water such as the Red Sea, Yellow Sea and Black Sea have been named for color. Oceanography has made use of color and clarity measurement to classify ocean waters using devices such as the simple Secchi Disc that is lowered into the water and observed visually and sophisticated spectrometers and radiometers. Until recently such measurements were made from ships that took a long period of time to cover any appreciable area of the ocean.

The ship measurements did show that ocean water color is related to parameters of great interest such as chlorophyll concentration and fish population, gelbstoffe or yellow stuff concentration as an indicator of salinity and sediments flowing into the oceans from rivers and streams. In general, waters rich in chlorophyll were found to be more productive of fish than those with lower concentrations since the chlorophyll is contained in phytoplankton, the beginning of the food chain in the ocean.

A number of oceanographers have made quantitative measurements relating ocean water color to its content, either biological or nonbiological, the most notable for the purposes of this paper being Yentsch^{1, 2, 3} and Clarke⁴. Yentsch's work, shown in Figure 1, in particular clearly shows the strong absorption bands of living phytoplankton near 440 to 450 nanometers and 670 nanometers. His measurements also show a clear relationship between gelbstoffe concentration and salinity of sea water, particularly near the mouths of rivers entering the sea.

Given the laboratory and shipboard measurements of oceanographers such as Yentsch and Clarke and the upsurge of remote sensing technology in the past decade, it was only natural that remote sensing of ocean color from vehicles other than ships, namely aircraft and spacecraft, be considered to help monitor the vast area of the world's oceans.

The pioneering work from aircraft was carried by Clarke, Ewing and Lorenzen⁵ in which they made spectroscopic measurements, from 400 to 700 nanometers, over waters with chlorophyll concentrations ranging from 0.3 to 3.0 mg/m³. Their measurements showed quite clearly that a useful determination of chlorophyll concentration could be made by remote sensing of ocean color and ushered in a new era of remote sensing of the ocean. Aircraft, however, cover small areas compared to the ocean area of interest, so it was a natural step to

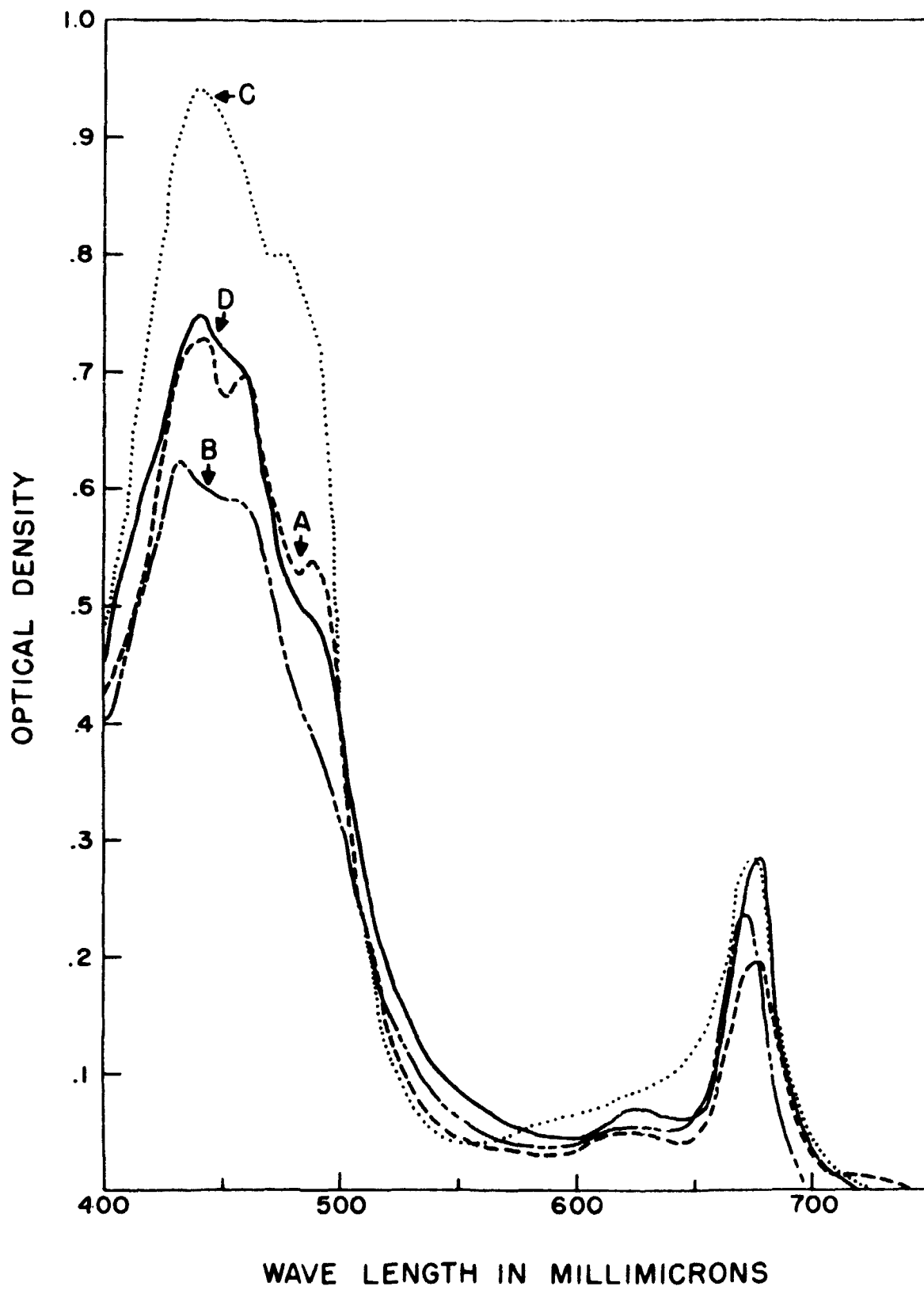


Figure 1. Spectral absorption of living phytoplankton (Yentsch-1959).

consider remote sensing of ocean color from a satellite to provide the large area coverage, in a reasonably short period of time.

Remote sensing of ocean temperature and color has already been accomplished from satellites such as TIROS, ITOS, Nimbus and ERTS but in every case the sensors were optimized for meteorological or earth resources sensing and the accuracies necessary for investigations such as chlorophyll determination were not available. Spectral bands are optimized for meteorological or earth resources purposes such as the ERTS Multi-Spectral Scanner with bands at 500 to 600, 600 to 700, 700 to 800 to 1100 nanometers where the blue, one of the most important spectral regions for ocean color, is not included.

In an attempt to define an ocean color sensor for spacecraft use, one serious limitation was recognized that had not been completely investigated in previous work, namely the effect of the atmospheric backscatter on such measurements. Clarke, Ewing and Lorenzen⁵ were limited by their aircraft to an altitude of 3 km and even at that modest altitude it was seen that atmospheric backscatter was causing an increase in radiance, as compared to 0.15 km measurements, and a decrease in contrast between water with high and low chlorophyll content. A comparison of Clarke, Ewing and Lorenzen's measurements at the two altitudes is shown in Figure 2. The question of whether a useful measurement of a parameter such as chlorophyll concentration could be made by measuring color through the entire scattering atmosphere had to be answered before a satellite experiment could be seriously considered. A goal of discriminating a change of 0.3 mg/M³ of chlorophyll was selected, representing a change of 10% of the normal range of ocean chlorophyll, and a series of high altitude aircraft experiments was started to determine if such a goal was achievable.

II. LEAR JET MEASUREMENTS

In the interest of speed and economy it was decided to conduct the first high altitude investigation from a small aircraft before considering a larger and more complex investigation. A Lear Jet, based at NASA Ames Research Center, was available for a short period of time, about one week, and was selected since it possessed an altitude capability of 15.24 km and was capable of rapid descent to facilitate comparison of high and low altitude measurements along the same track before the sun angle could change appreciably.

A rapid scan, 0.25 meter Fastie-Ebert spectrometer was utilized to scan 400 to 700 nanometers in 2 seconds with a spectral bandpass of about 0.5 nanometers. The scan drive utilized was a cam driven sine drive to produce a scan rate of wavelength linear with time. The detector was a photomultiplier whose output

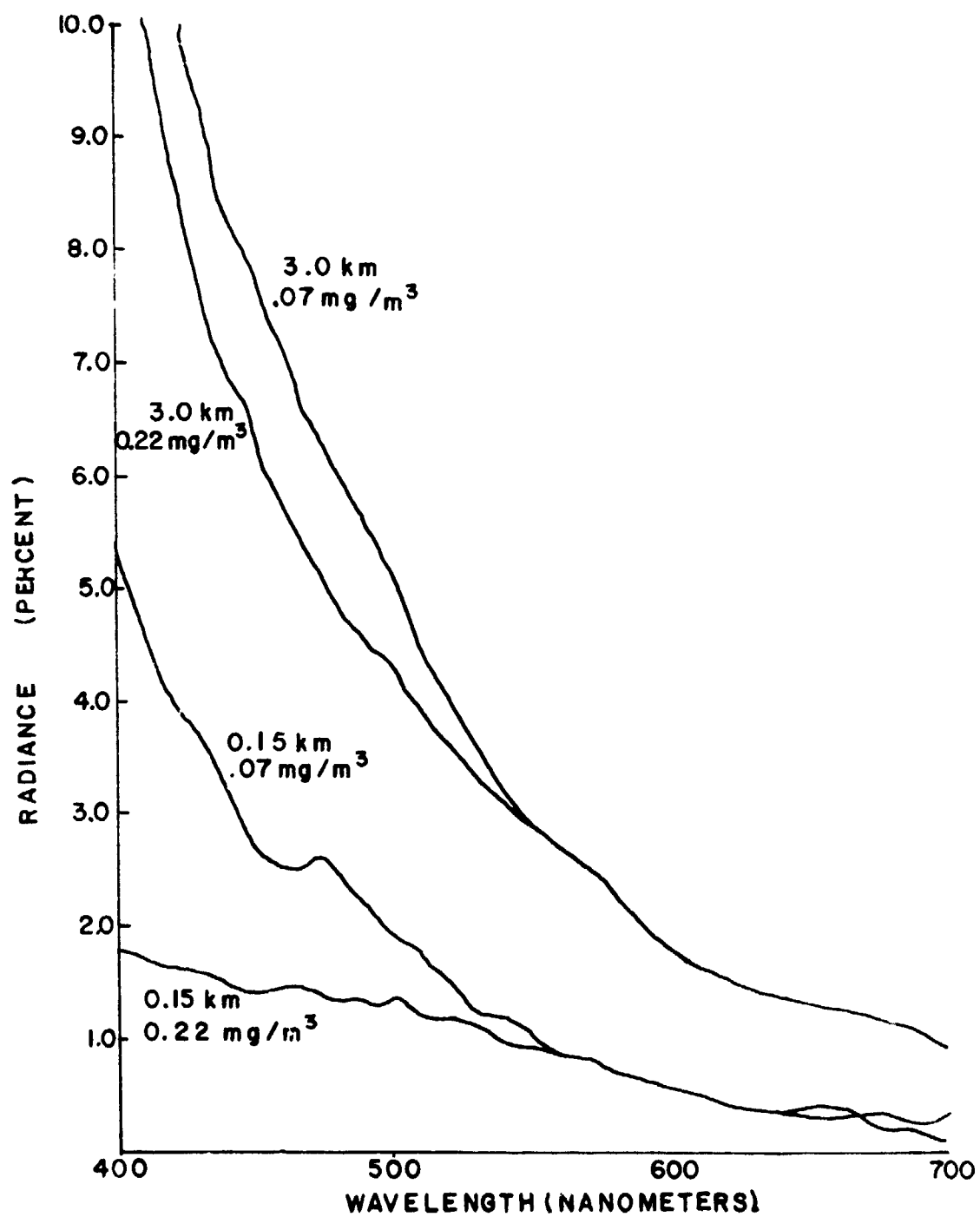


Figure 2. Reflectance vs wavelength as a function of altitude and chlorophyll concentration (Ewing et al.).

was detected by a high speed electrometer and recorded by a strip chart recorder. The data was digitized off the strip chart recording and then corrected by computer to plots of exitance vs wavelength. The term exitance is used because of the nature of the instrument calibration procedure. The Fastie-Ebert spectrometer was calibrated using an internally illuminated integrating sphere whose spectral radiant emittance was in turn calibrated against an NBS standard lamp. Since the ocean and atmosphere do not emit, but reflect and scatter the incident solar energy, we will refer to the measurements of ocean color as exitance rather than emittance or radiance.

The Instantaneous Geometric Field of View (IFOV) of the Ebert was 3.8×3.8 milliradians as determined by the telescope focal length and the entrance aperture of the spectrometer serving as a field stop. At low altitudes, such as 0.3 km, it was found that the narrow field was spatially resolving waves and causing a noisy signal. At 0.91 km enough spatial integration occurred to smooth out the signal.

The area chosen for the Lear Jet flights was over the Catalina Channel off Los Angeles in August of 1971 where strong chlorophyll gradients were expected to occur due to sewage outflow from Los Angeles and Orange County and where an oceanographic vessel from the Visibility Laboratory of the Scripps Institution of Oceanography would be making surface truth measurements. As so frequently happens, the expected did not occur and no reasonably strong chlorophyll gradients were found indicating a lack of support for our project by the citizens of Los Angeles and Orange County.

On August 5, 1971, a clear day occurred allowing a long flight path, free of clouds, from the beach at San Clemente, California, past the southern tip of Catalina Island. Chlorophyll measurements were not available along the track since the ship had not traversed the track and its speed made it impractical to cover the track in a reasonably short period of time. The great difference in speed between aircraft and surface ships has been found to be one of the biggest problems in correlating surface truth measurements and aircraft measurements.

Chlorophyll concentration is known to vary diurnally so a series of measurements made by a slow moving ship will not truly represent the chlorophyll distribution, along a track of many miles, as it would appear at any one time of the day. The only solution seems to be a number of ships, each covering a small portion of the track.

In our case the ship was 3.5 miles South East of the southern tip of Catalina in water with a measured chlorophyll concentration 0.45 mg/m^3 from a surface sample and 0.35 mg/m^3 from the ships water system. The aircraft overflew the ship at two altitudes, 14.90 km and 0.91 km, with measured spectra as

shown in Figure 3. The sharp absorption lines seen are Fraunhofer Lines of the solar spectrum. The two spectra illustrate the problem that is encountered in attempting to measure the color of a relatively low reflector such as water through a scattering atmosphere.

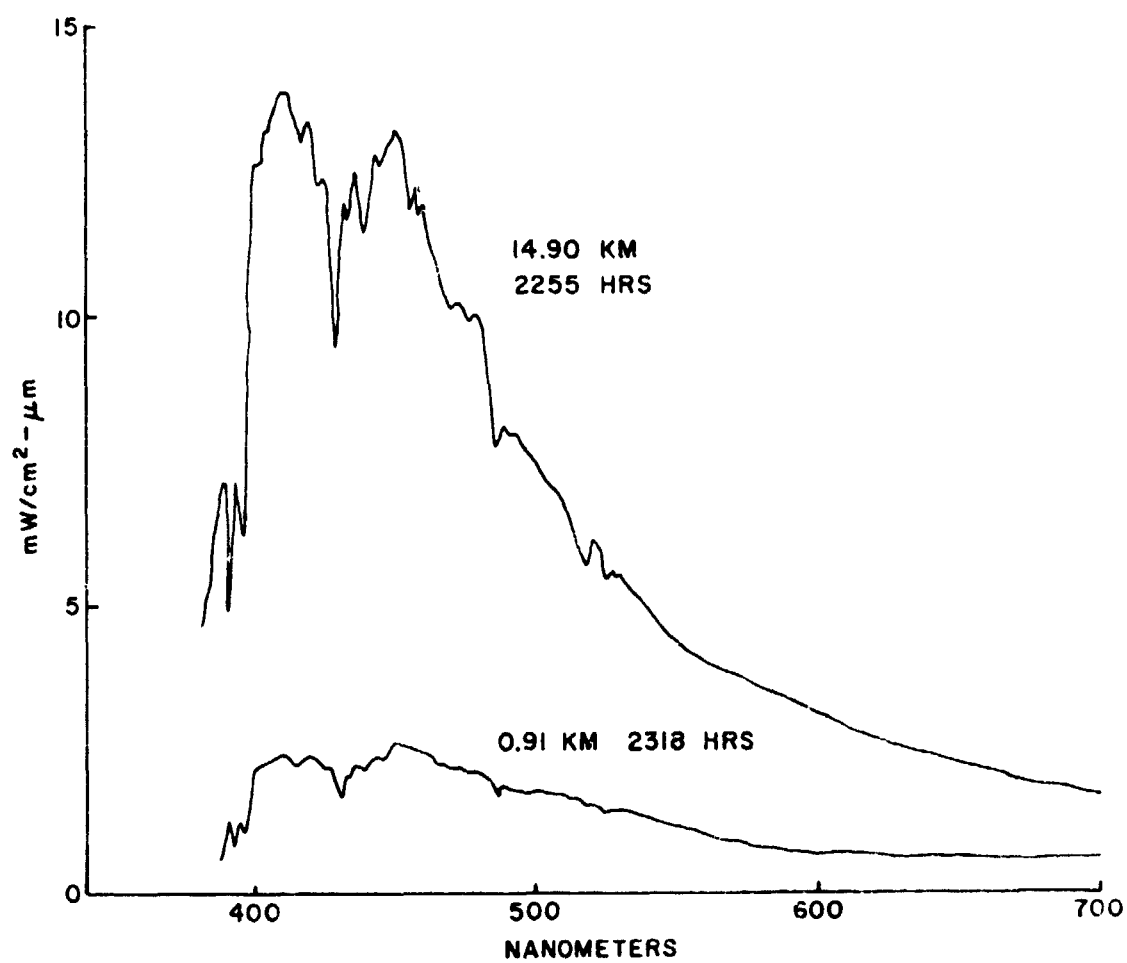


Figure 3. Lear Jet spectra at high and low altitudes.

The upwelling reflected sunlight at 14.90 km is about five times as intense as that at 0.91 km and certainly some of the sunlight reflected by the water was scattered out of the column of view on its upward passage through the atmosphere. Some idea of what portion of the sunlight reflected by the ocean reaches the top of the atmosphere unscattered may be estimated by comparing contrasts found in the high and low altitude measurements. This was done at 450 nanometers with the result in Figure 4. In the figure, the exitance is plotted, along the same track, as seen at the two altitudes. The exitance measured at 0.91 km is multiplied by a factor of 5 to facilitate comparison of contrast with that seen at 14.90 km.

The contrast observed at 14.90 km is, as expected, reduced by the introduction of atmospheric backscatter but the degree of contrast reduction is about a factor of 10, twice that of the increase in total upwelling radiance. This indicates that approximately half of the sunlight, scattered by the ocean, was scattered out of the column viewed by the spectrometer on its upward passage through the atmosphere.

Even though the contrast was severely reduced by atmospheric attenuation and scattering the color change at the surface is reasonably well represented in the high altitude data, at least at 450 nm. Since the blue is one of, if not the most important spectral region for ocean color measurement and atmospheric scatter is more intense than at longer wavelengths where other ocean color measurements would be made, it was concluded that there was enough potential to organize a larger, more comprehensive ocean color expedition.

Another problem was noted in the Lear Jet experiments by use of downward looking color cameras. Sun glint, specular reflection from wave facets, was found to be intense even with solar zenith angles as high as 55° . Since glint obscures the true color of the water beneath, and thus information about the content of that water, steps are necessary to avoid its effects. Fortunately the glint intensity diminishes rapidly when viewed off nadir and away from the sun so instruments to measure ocean color should be equipped with pointing capability to minimize glint effects.

Using this and other data, Curran⁶ calculated the effects of varying aerosol depths on the measurement of ocean color and concluded that the accuracy of chlorophyll determination was partially limited by the ability to determine aerosol optical depth.

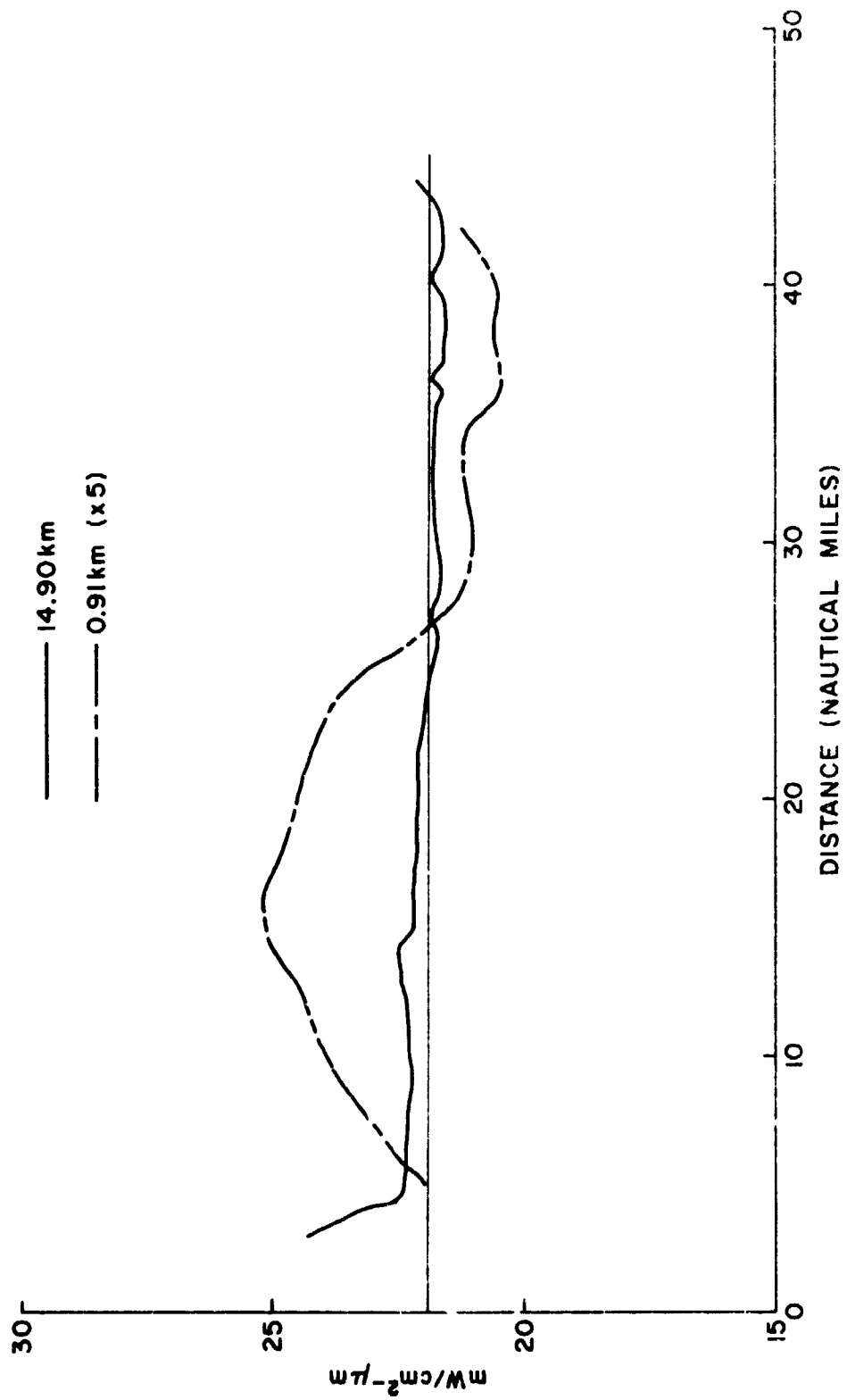


Figure 4. Exitance at 450 nm vs location at high and low altitudes.

III. CONVAIR 990 MEASUREMENTS

The results from the Lear Jet flights left unanswered a number of questions that had to be answered before ocean color measurements could be carried out from a spacecraft. The lack of chlorophyll gradients off Los Angeles prevented a determination of what magnitude of gradient could be detected and what quantitative accuracy would be possible with measurements through the atmosphere. The Lear Jet flights did show, however, that contrast due to changes in surface reflectance was reasonably represented by high altitude measurements so it was decided to conduct a more comprehensive series of investigations utilizing the NASA Convair 990 aircraft with extensive surface truth support.

For these investigations a number of sensors were mounted on the CV990 in addition to sensors routinely carried including a Texas Instruments RS 310 scanning infrared radiometer, a nadir looking infrared radiometer and sensors to determine outside air temperature, aircraft speed, direction attitude and location.

The results reported here were measured with the same Gastie-Ebert spectrometer used in the Lear Jet flights. The difference was that, on the CV990, the data was recorded on both digital and analog tape recorders as well as strip chart recorders and the telescope was removable for low altitude flight. At high altitude the IFOV was 3.8 milliradians square, as in the Lear Jet flights, and at low altitude it was 0.24×0.24 radians. The removable telescope solved the problem encountered with resolution of single waves in the Lear Jet flights and allowed operation at altitudes down to 0.3 km.

Attempts were made to conduct measurements over a wide variety of conditions during the time period June 28 to July 24, 1972, with the risk of weather interference always a factor. Scheduling flights and support for a four engine jet and accommodations for the large number of people involved requires a rigid schedule with little room for change. Flights and surface truth support measurements were scheduled for the San Francisco area, the Boston-Cape Cod area, Africa from the Canaries to Dakar, off the North Carolina Coast out to the Gulf Stream, the vicinity of Florida including the Gulf of Mexico and the Sargasso Sea and the Mississippi Sound.

Cloud cover was the biggest single problem with air traffic control another significant problem. The one area where gelbstoffe (yellow stuff) measurements were expected to be of particular interest was off the mouth of the Merrimac River entering the Atlantic at Newbury-Port, Massachusetts. In the two days of flights scheduled for that area clouds prevented observations on the first day, July 7, 1972, and air traffic control problems prevented overflights of the area

containing the gelbstoffe gradients measured by Prof. Yentsch and a group from the University of Massachusetts on the second flight on July 8, 1972.

The measurements reported here are those made where the weather was reasonably clear and chlorophyll gradients were found to exist. Measurements of gelbstoffe by color sensing will be attempted at a later time.

A. Measurement Off North Carolina

The Atlantic Ocean off North Carolina was chosen for a series of flights from the shoreline, East across the Gulf Stream, along the 36°N parallel of latitude. The RV Annandale, manned by personnel of the Marine Science Consortium, provided surface truth support including surface temperature, vertical temperature profiles, and measurement of chlorophyll and phaeophytin. Weather, as always seems the case, was the biggest problem encountered. Flights were conducted in the morning to minimize both sun glint and cloud cover but cloud cover, principally cumulus systems, was a problem. On July 17, 1972, a relatively clear track was open along the 36°N parallel and a set of high and low altitude flights conducted.

The Annandale had made chlorophyll measurements along the track and the aircraft nadir looking infrared radiometer made surface temperature measurements along the track. Both are plotted on Figure 5. The x's on the chlorophyll plot show typical dispersions for surface chlorophyll measurements. The edge of the Gulf Stream is clearly visible, in the temperature plot, at around 74°W longitude with a corresponding dip in chlorophyll. Ship measurements were not made inshore of $74^{\circ}46.9'\text{W}$ to avoid the treacherous shallows of Cape Hatteras.

Spectra were taken at two second intervals along 36°N at 11.3 and 0.3 km altitude. Two high altitude spectra are shown in Figure 6 at two locations with chlorophyll concentrations as shown. The spectra are valuable in that they provide a complete picture of the exitance as a function of wavelength but, for ocean color mapping from satellites, multi-spectral imagery will be obtained, in selected bands, not complete spectra. For this reason it was decided to work in a format where the exitance at particular wavelengths is plotted along the track and treated as the output of one scan line of an imaging scanner.

The shape of the chlorophyll absorption curve suggests that chlorophyll information might best be extracted from radiometric data by ratio techniques rather than single wavelength measurements since absorption at 550 to 600 nm is relatively independent of chlorophyll concentration and could serve as a normalizing point. Arvesen et al.⁷ have reported measurements made with a two channel differential radiometer with bands at 443 and 525 nm, and obtained good agreement with surface truth measurements in low altitude experiments.

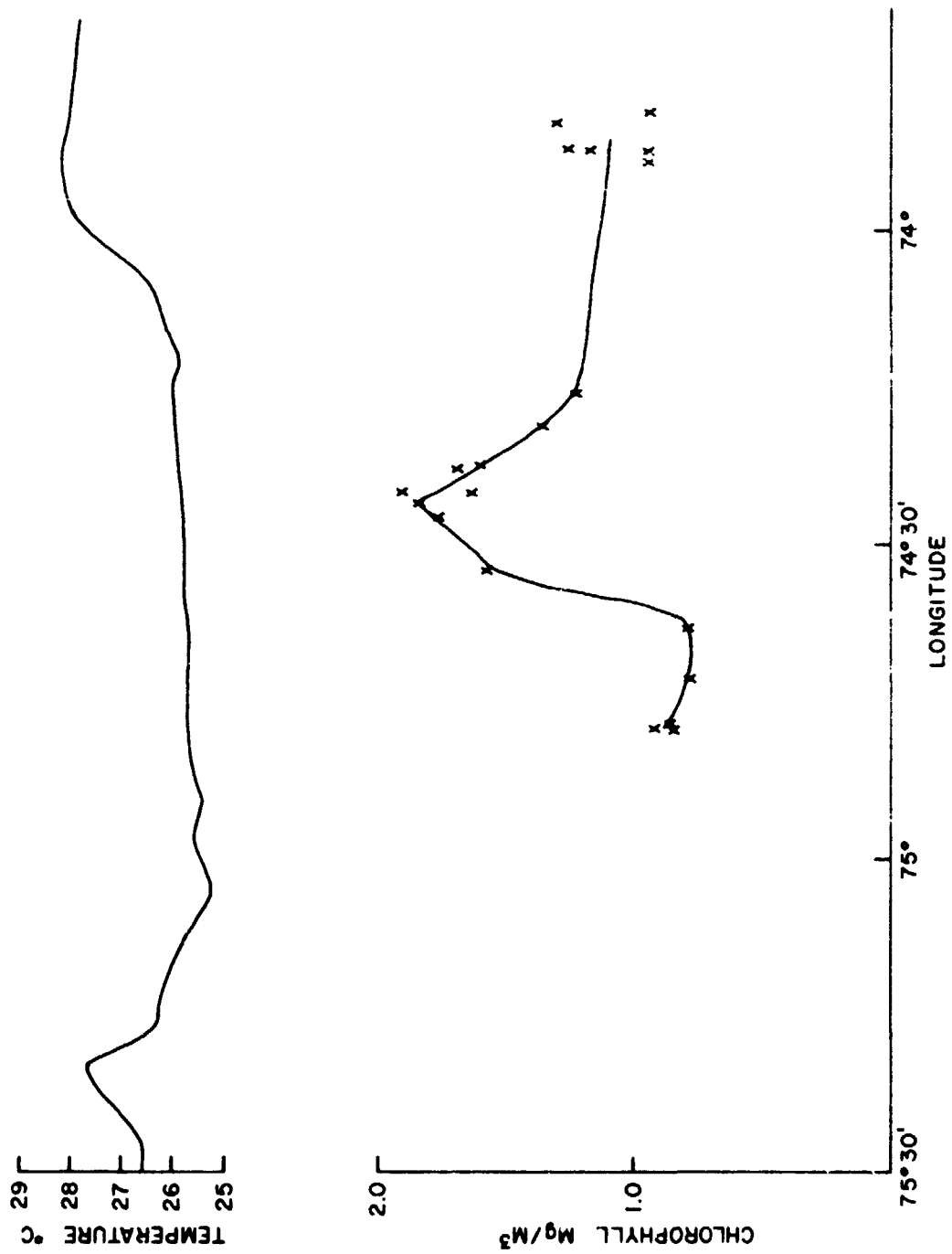


Figure 5. Temperature and chlorophyll measurements along track off North Carolina.

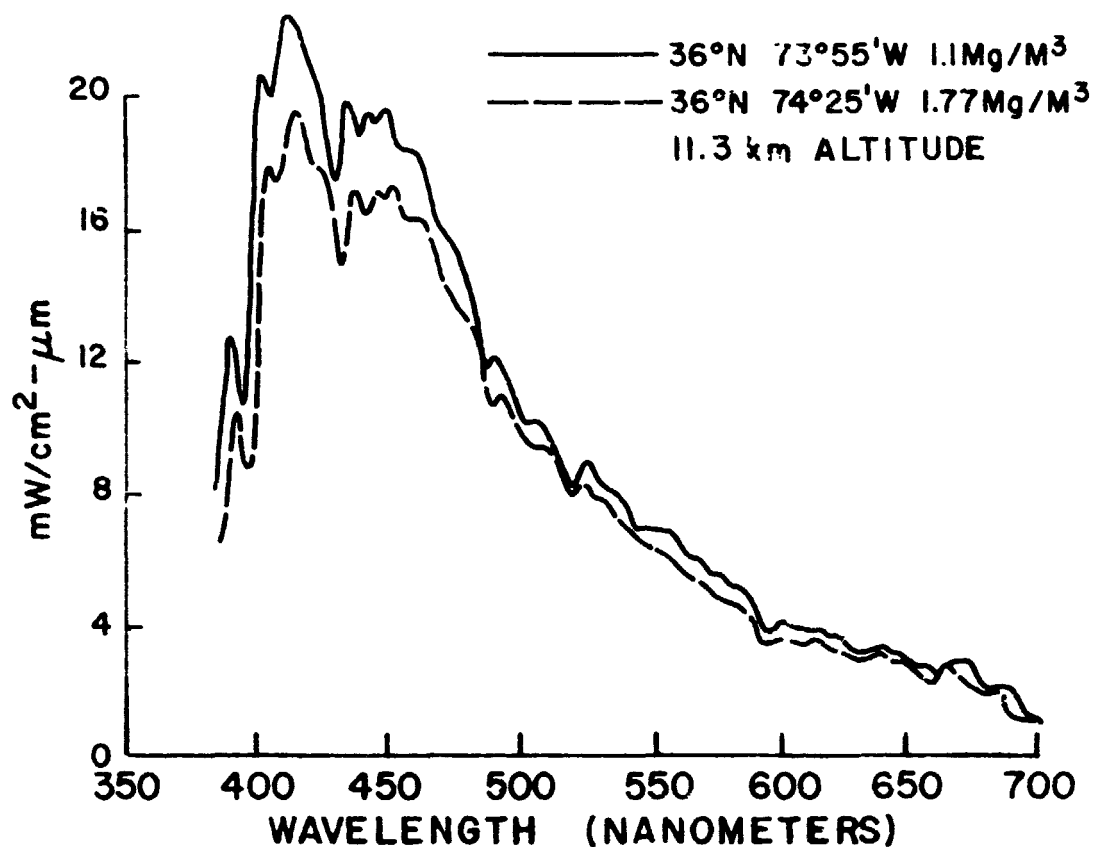


Figure 6. High altitude spectra for different chlorophyll concentrations.

The use of ratios offers the potential to minimize effects of atmospheric changes by always referring to a spectral band that is relatively unaffected by changes in chlorophyll content in the water. Figure 7 shows the absolute value of ratios of exitances along the track for four different cases compared with the surface truth measurements. The simple two exitance ratios show fair agreement with the surface truth measurements of chlorophyll and may be more representative of the chlorophyll distribution during the actual flight than the ship measurements since the ship took three days to traverse the track. At any rate, ratios do show that the chlorophyll gradient was detectable from high altitude measurements and that a chlorophyll maximum, such as occurred around 74°34' West, can be detected through a scattering atmosphere.

B. Measurements Off San Francisco

Since the CV990 aircraft was based at Ames Research Center, Moffett Field, California, it was decided to conduct the flights in that area as a shakedown. It

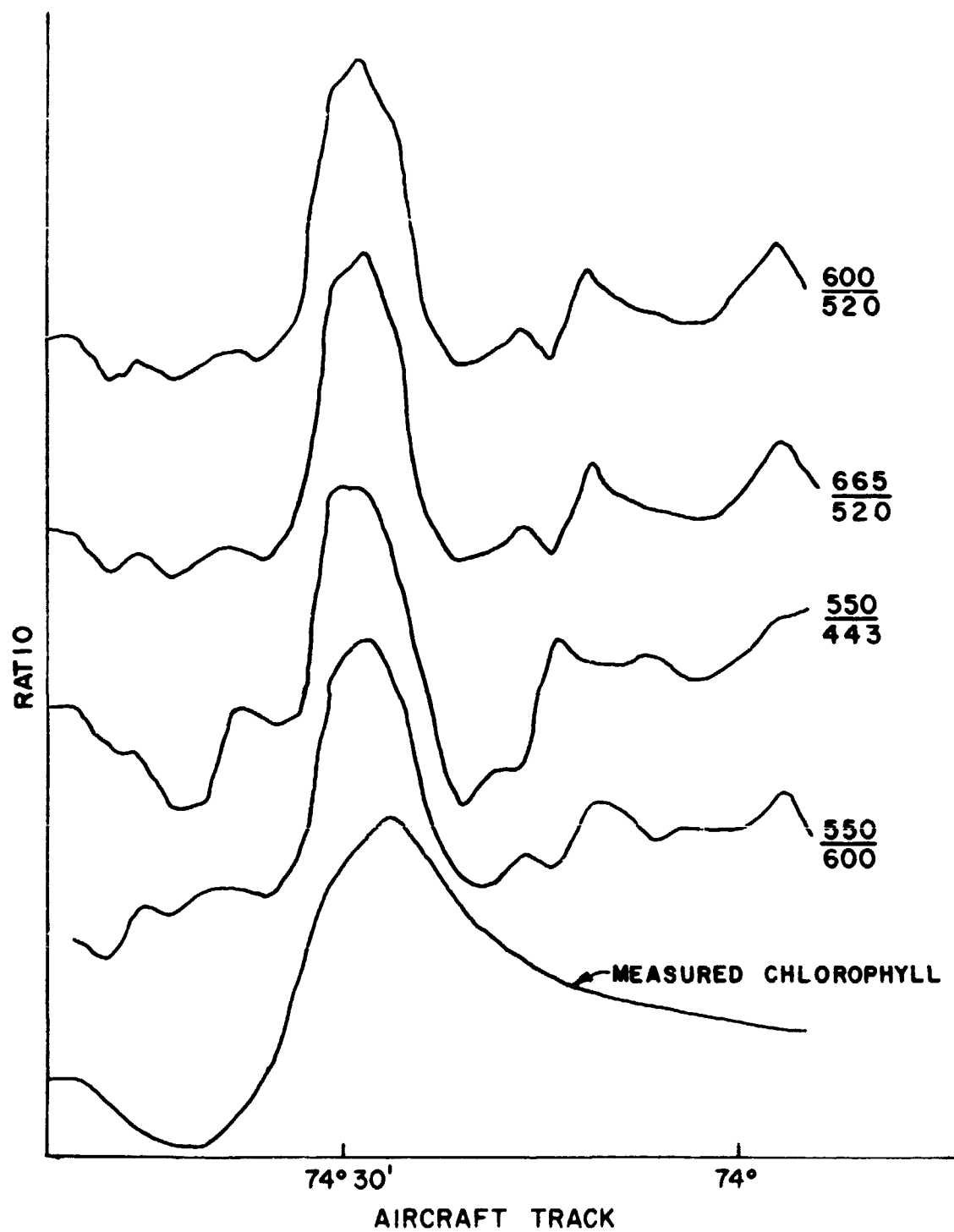


Figure 7. Ratios of selected wavelengths and ground truth vs position.

was decided to deploy two research vessels, the R/V Falcon and the Shipmates along a track from the Golden Gate Bridge generally West to 36°N, 127°W. The Falcon covered most of the Western end of the track while the Shipmates covered the end of the track near the Golden Gate Bridge where the largest chlorophyll gradients were expected and found.

Figure 8 shows the spectra measured, at 0.3 km altitude, over two areas with a greatly different chlorophyll concentration. The high chlorophyll area was just off the bridge and the lower chlorophyll area some 57 nautical miles out. The day was clear with a haze noticeable below 0.3 km apparently due to wind driven spray from a wind that varied from about 2 knots at the bridge to velocities in the forties at the Western end of the track. Wind speed is measured by the aircrafts Doppler Navigation System at the aircraft altitude.

The exitance measured at high altitude, 11.3 km, and low altitude, 0.3 km, is shown in Figure 9 for 443 and 550 nanometers. The ratio of exitances at 443 and 550 nm is shown in Figure 10 compared to the chlorophyll concentrations

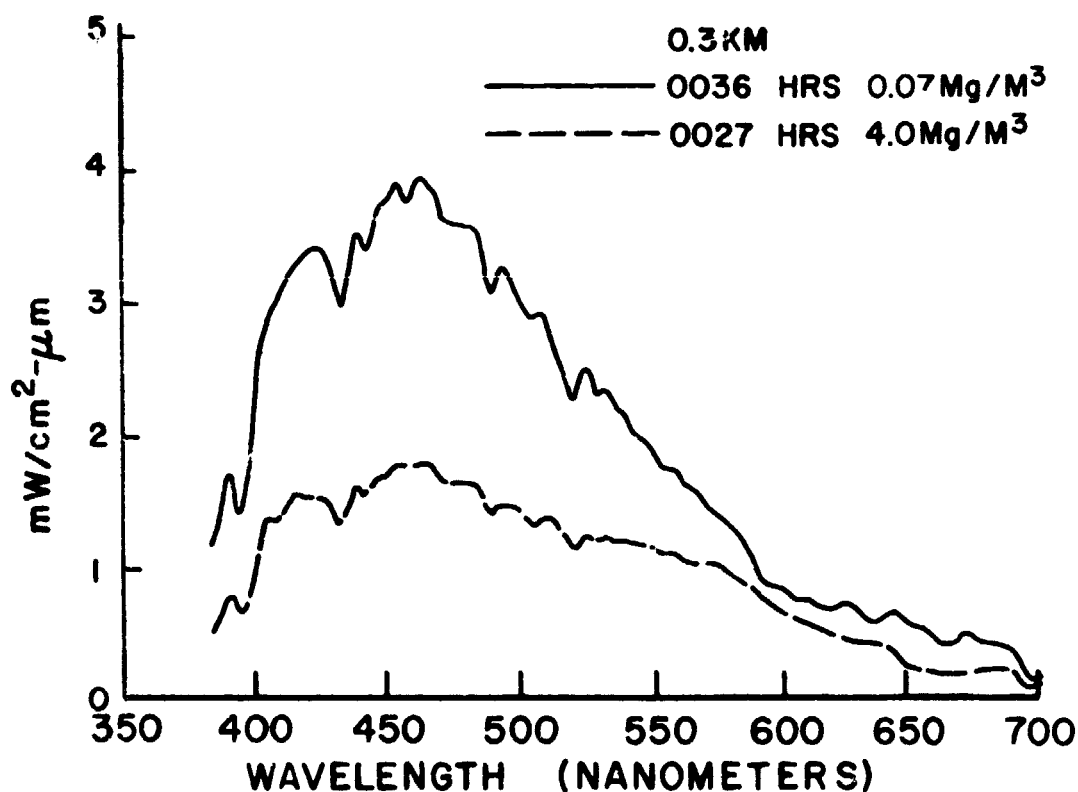


Figure 8. Low altitude spectra for two different chlorophyll concentrations.

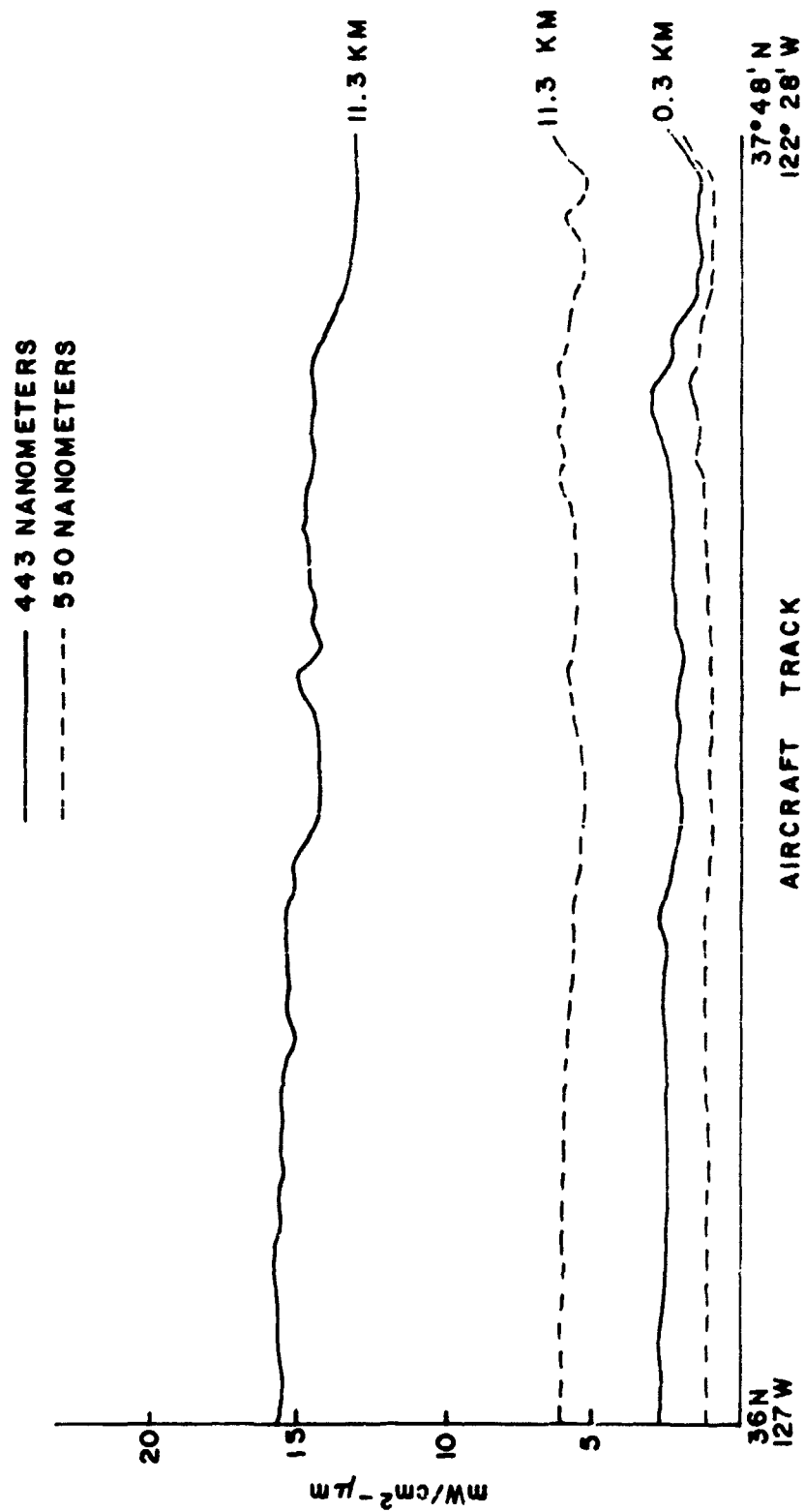


Figure 9. Exitance along flight path for 443 and 550 nm at high and low altitudes.

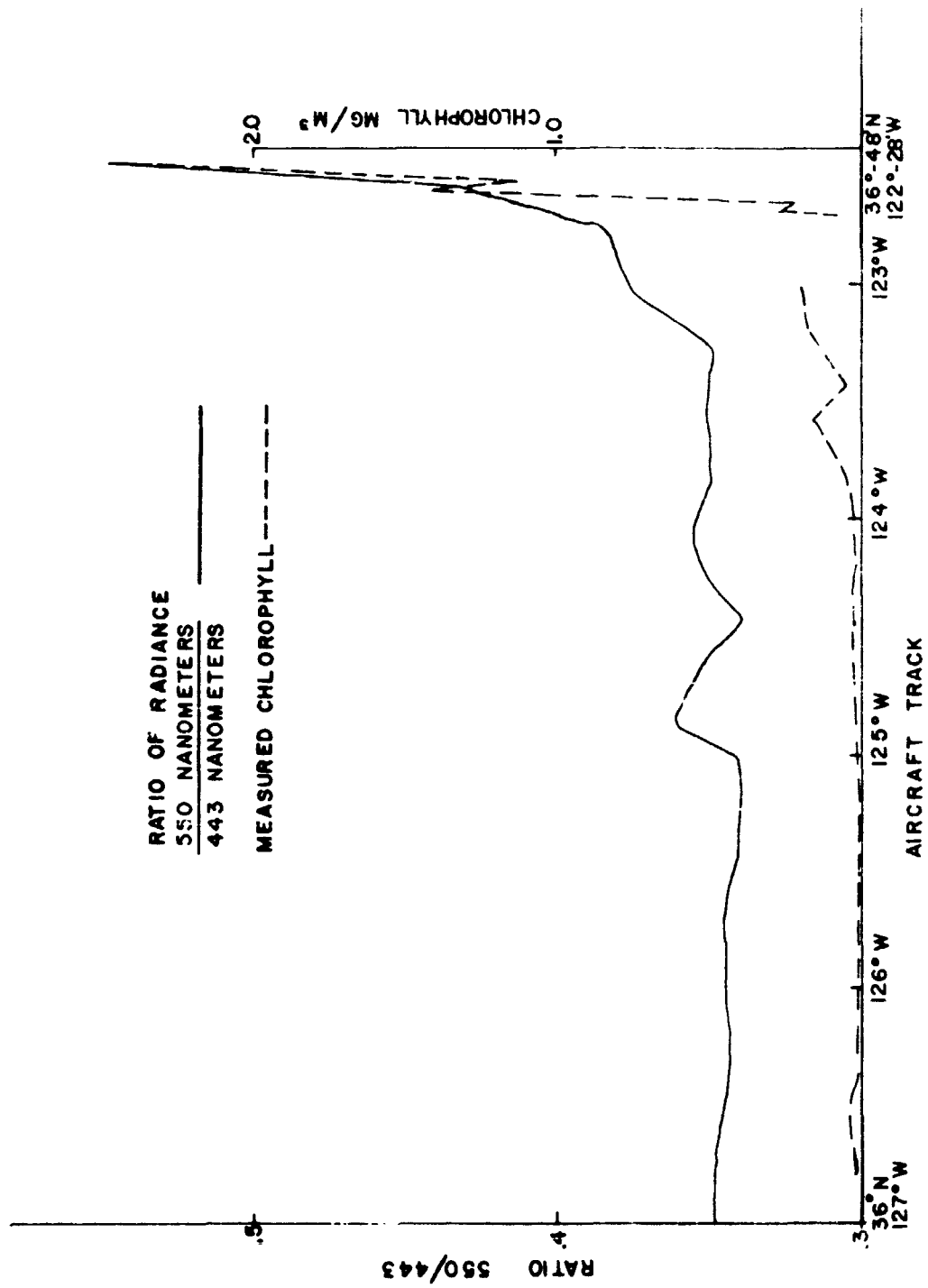


Figure 10. Ratio of 550 to 443 nm and measured chlorophyll ground truth along flight path.

measured by two vessels on the surface. The gradient of chlorophyll is much sharper than that seen in the Atlantic off North Carolina and the correlation quite good as would be expected for such a well defined change in chlorophyll and color. The chlorophyll rise most probably results from outflow from San Francisco Bay and has, subsequently, been observed in pictures of the area taken with the ERTS Multi-Spectral Scanner (MSS). The ERTS MSS has no blue spectral bands and its gain settings are optimized for land surface targets, not oceans, so detection of the feature observed from the aircraft by the ERTS MSS is encouraging for use of a spacecraft scanner optimized for ocean color measurement.

C. Measurements Off Africa

The Convair 990 was involved in a cooperative program with Russian oceanographic vessels off the West Coast of Africa in July 1972, providing the opportunity to measure ocean color off Africa. Cloudy weather prevented any useful color observations near the Russian vessels located South West of Dakar or over a French research vessel North East of the Canary Islands. A stretch of clear weather was found between 19° and 25° N latitude, just off the West Coast of Africa and over a popular fishing area around 20° 07' N, 17° 38.8' W.

Surface truth measurements were not available in the area of clear weather but interesting comparisons could be made with the chlorophyll measurements made by Arvesen⁸, at low altitude, with the two channel differential radiometer described in (7) and the surface temperature measurements made with the infrared radiometer at low altitudes. The distribution of fishing vessels also provided an interesting commentary on the relationship between water color, temperature and fisheries potential.

The surface water temperature and chlorophyll, as inferred from Arvesen's measurements, are shown in Figure 11 together with arrows indicating the location of the fishing fleet. Except for the sharp maximum of chlorophyll to the North of the fishing fleet the fleet is fairly well centered on the highest chlorophyll and lowest temperature area. The relationship between the chlorophyll and temperature is not surprising since, in many cases, cold water upwellings bringing nutrients from lower levels and are responsible for chlorophyll growth.

Spectra from 11.3 km altitude, Figure 12, illustrates the difference detectable at high altitude and clearly shows the "hinge point" at 550 nanometers relatively unaffected by the variation in chlorophyll content. Exitances at 443 and 550 nanometers for the two altitudes flown are shown in Figure 13. Ratios of exitances shown in Figure 14 show agreement with the trend measured by Arvesen.

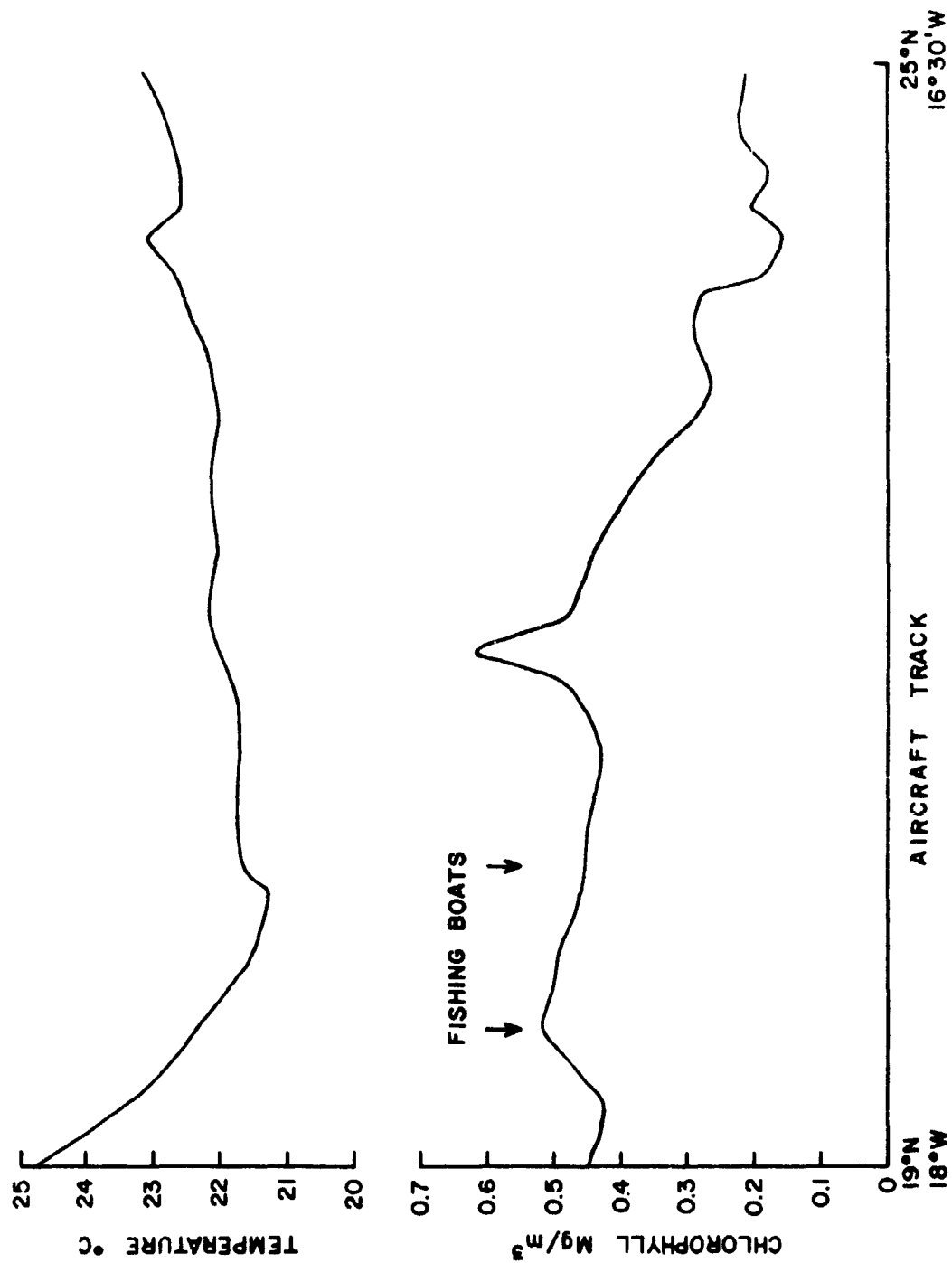


Figure 11. Inferred chlorophyll concentration (Arvesen) and temperature vs aircraft track.

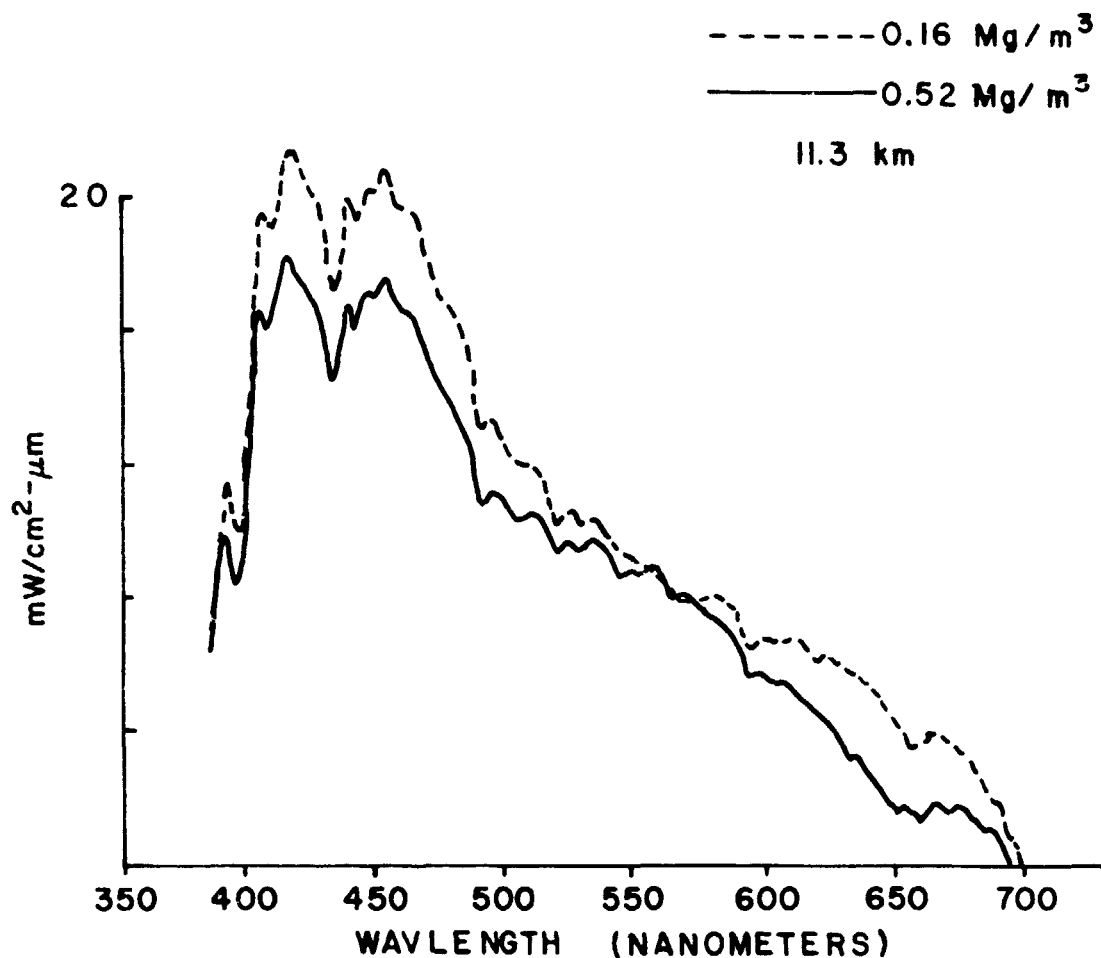


Figure 12. High altitude spectra for two chlorophyll concentrations.

The relatively small change in chlorophyll, of the order of 0.3 Mg/m^3 was detectable and changes of 0.1 Mg/m^3 are resolvable showing that the goal of resolving gradients of 0.3 Mg/m^3 can be achieved, at least under the atmospheric conditions prevailing the day the measurements were made.

D. Measurements Over Mississippi Sound

On July 24, 1972, flights were conducted over the Mississippi Sound along a East West track 60 nautical miles in length. Extensive surface truth measurements were carried out by personnel of the Earth Resources Laboratory of the NASA Mississippi Test Facility. Chlorophyll was measured at 24 stations along the track almost coincident with overflights of the Convair 990. Unfortunately, the day was quite hazy due both to smoke from onshore sources and

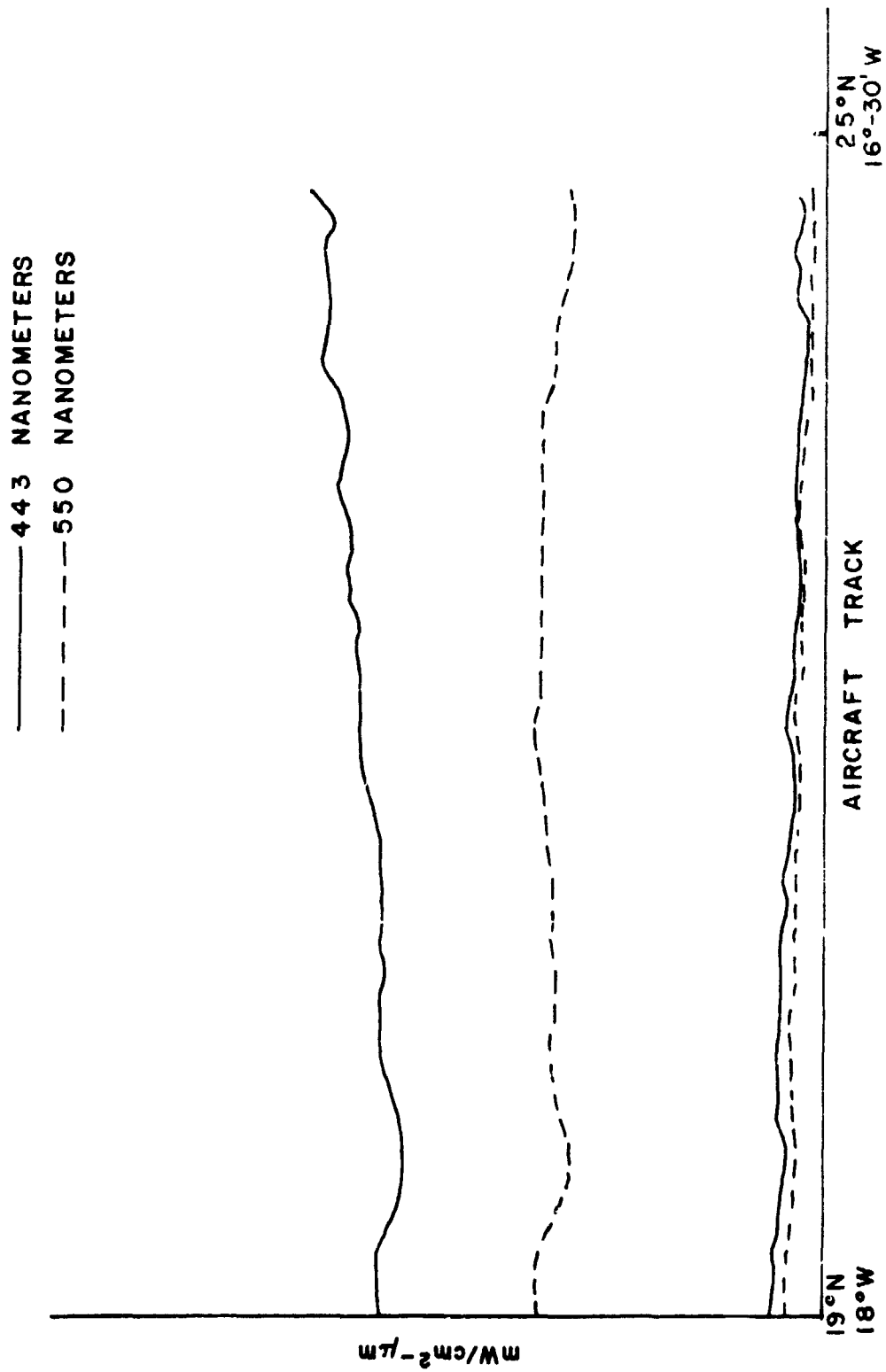


Figure 13. Exitance along flight path for 443 nm and 550 nm at high and low altitudes.

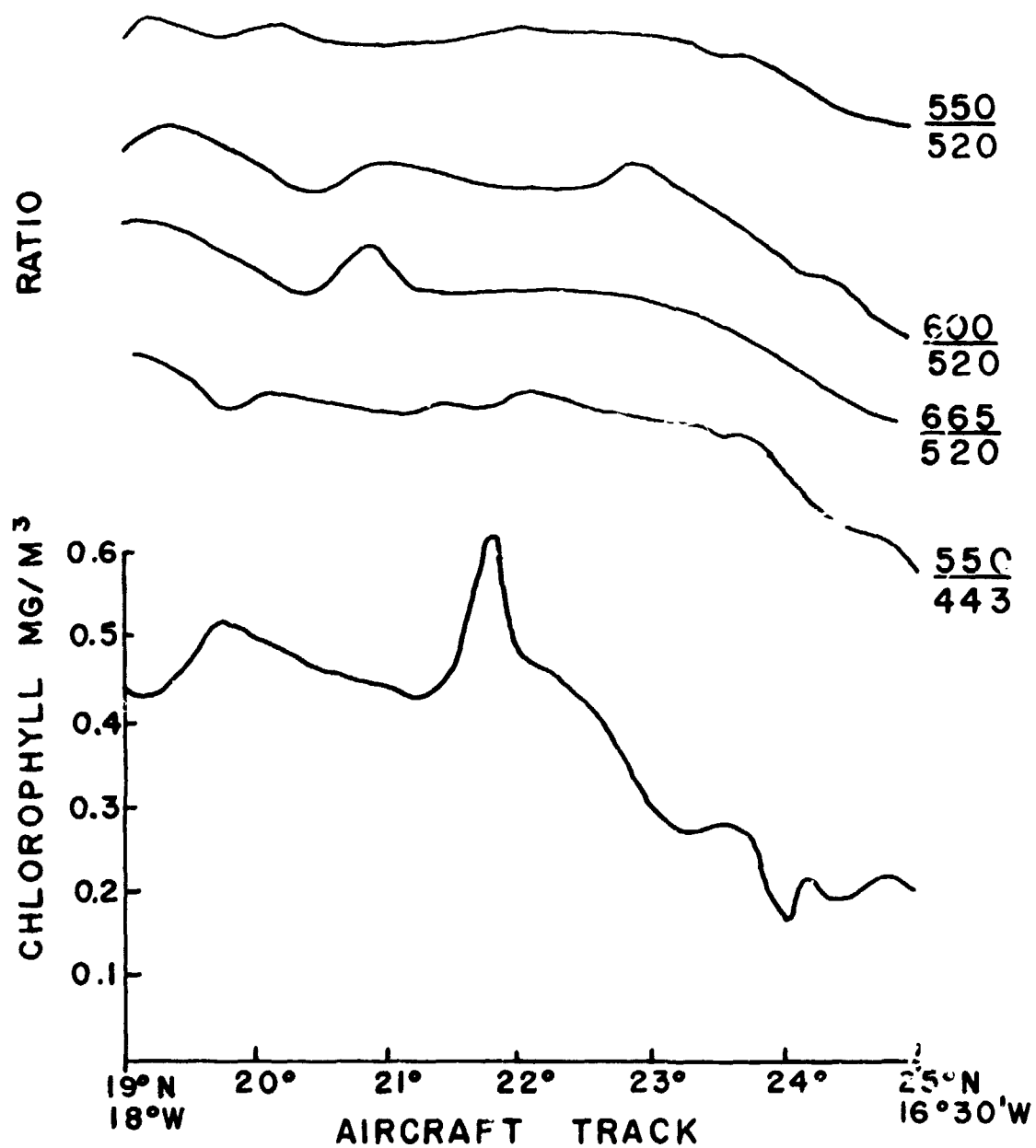


Figure 14. Selected ratios and inferred chlorophyll ground truth along aircraft track.

natural haze. The unfortunate atmospheric conditions did, however, present the opportunity to test how well ocean color could be detected through a thick haze.

The chlorophyll concentrations and surface temperatures measured by the surface ships are shown in Figure 15 for the flight path covered. The water depth in the Mississippi Sound is shallow, about 2 to 7 meters so upwelling is relatively unimportant in supply of nutrients to phytoplankton and there is little correlation between temperature and chlorophyll concentration.

Figure 16 shows the ratios of exitances measured at several wavelengths compared to the chlorophyll concentration measured at the surface. Despite the hazy atmosphere the ratios, especially $550/413$ and $665/520$, do agree with the positions of maximum and minimum chlorophyll concentrations.

IV. CONCLUSIONS

The conclusion that useful ocean color measurements can be made from space has already come from the analysis of data from the ERTS Multi-Spectral Scanner. The data presented here extends that work and shows that an experiment, aimed exclusively at ocean color measurement, is desirable and that reasonably small changes in chlorophyll can be detected through our atmosphere. Such an experiment would utilize spectral bands and radiance sensitivities optimized for water rather than land surfaces and be capable of detecting more subtle changes in ocean color than the ERTS sensor.

Remote sensing of absolute chlorophyll concentrations, as opposed to sensing spatial changes, is complicated by many factors such as varying atmospheric aerosol scattering and varying surface roughness. Efforts are underway to develop techniques to remotely sense such variable so that, eventually, a set of sensors may attack the problem of absolute chlorophyll concentration measurements.

ACKNOWLEDGEMENTS

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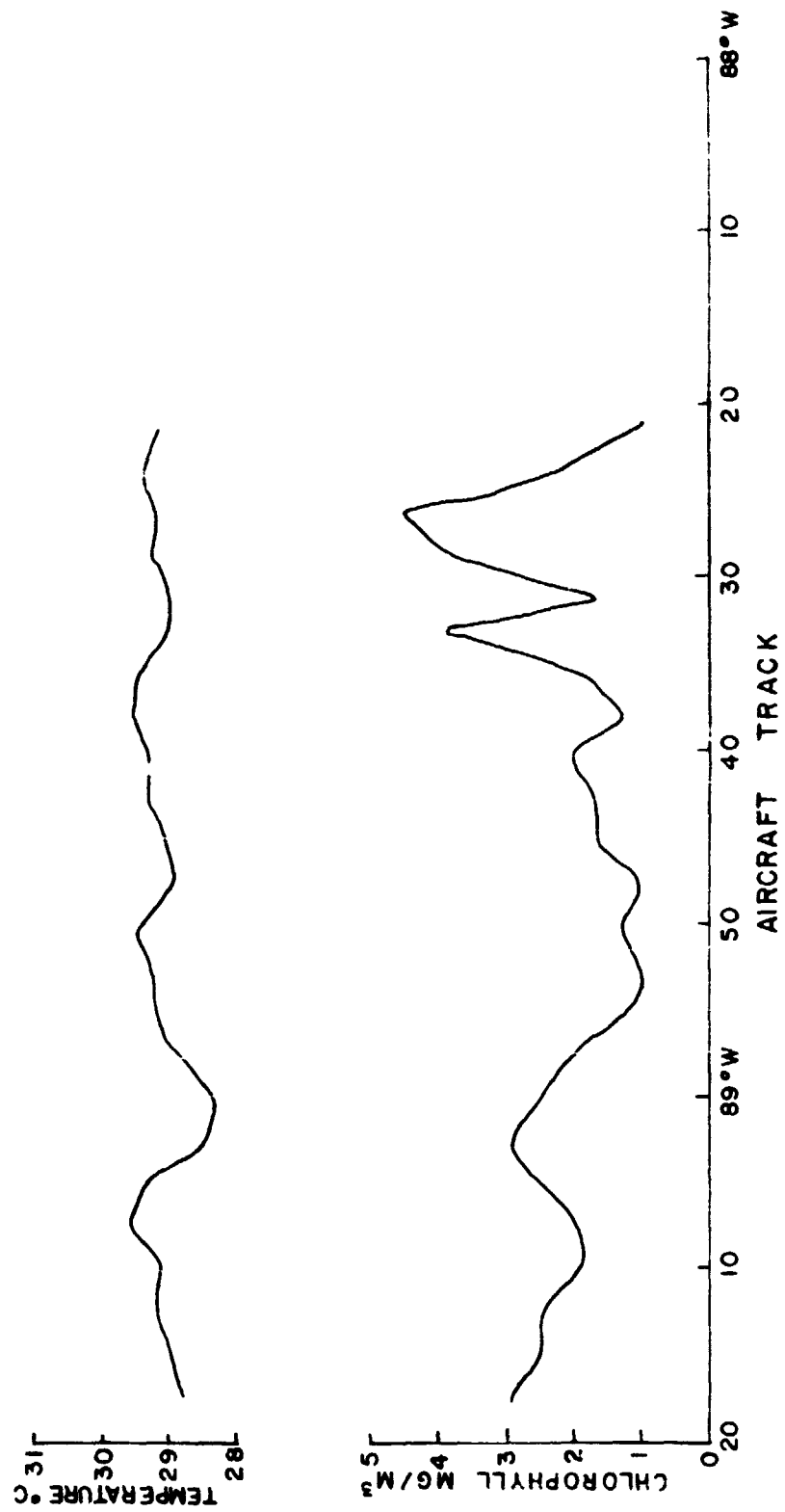


Figure 15. Chlorophyll concentration and temperature along aircraft track.

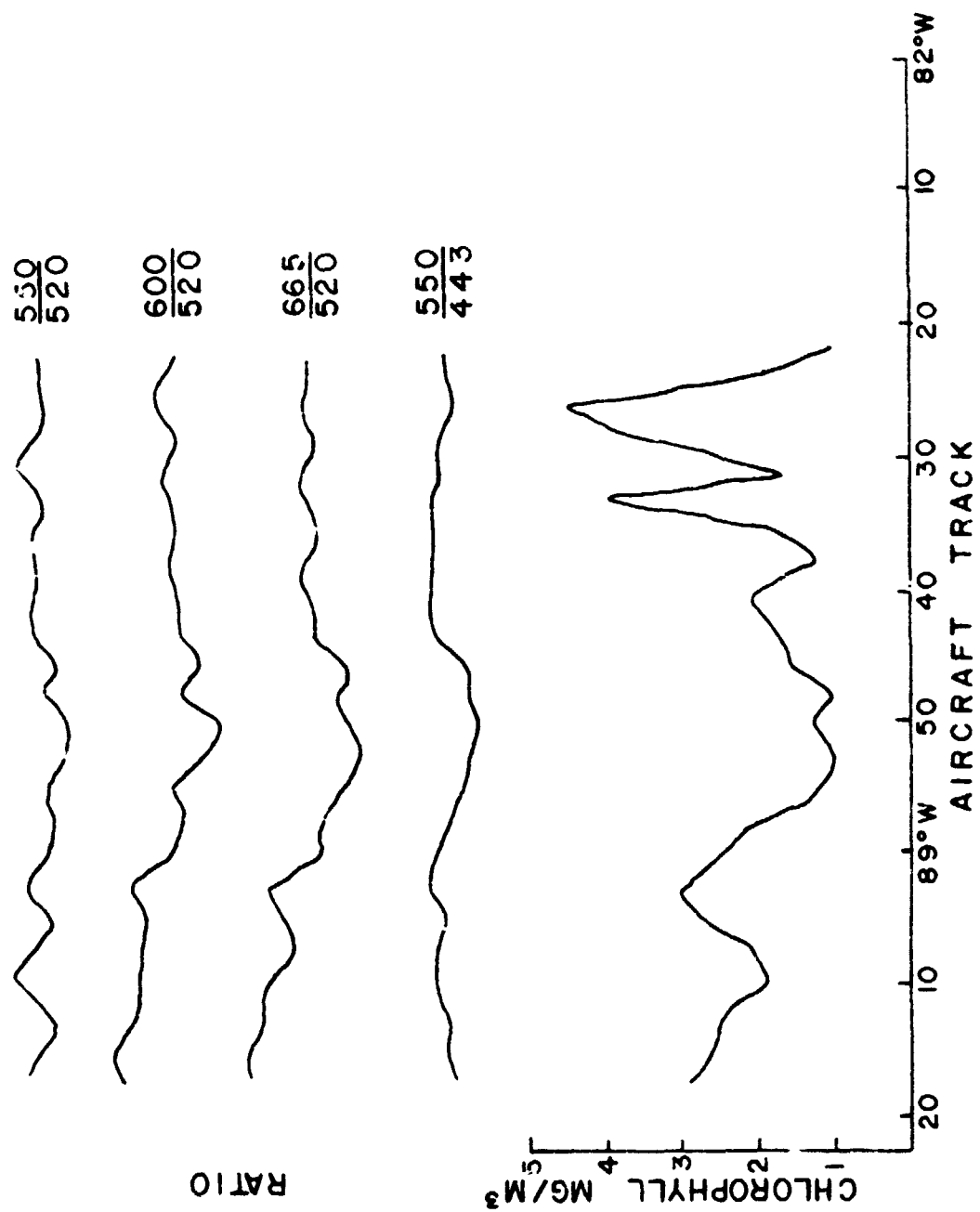


Figure 16. Selected ratios and chlorophyll ground truth along aircraft track.

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